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Patentanmeldung Nr.   Patent application No.   Demande de brevet n°

03078841.8

PRIORITY DOCUMENT

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For the President of the European Patent Office

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Holographic data storage 2

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Holographic data storage 2

Staggered data structure in holographic storage systems

Introduction

Form recording data in holographic datastorage systems, data bits organized in
pages are formed by a 2 dimensional grid of bits (for example using a light modulator
5   with a two dimensional array of individually addressable elements (often also
referred to as pixels)), which are either on or off. Unlike conventional optical storage
systems like CD and DVD, the use of run length limited codes is not pursued, not
because of the fact that this in principle impossible, but due to practical reasons. In
holographic systems, a 2-dimensional pixilated light modulator can be used to
10   transmit portions of a so-called data beam resulting in an encoded data beam, which
after interference with a reference beam can form a diffractive structure in a suitable
storage medium. Since the pixels in these light modulators determine the data bits,
and the system will be designed to be diffraction limited in order to achieve the
highest density, datapages consist of individual dots (data bits). Also other types of
15   light modulators (like reflective) can be used.

Problem

Consider the figures below. Drawn on top is a conventional structure of data pages.
This is not the most efficient way to make use of the available area in the medium
20   and hence could results in a too low bitdensity.

Solution and some embodiments

It is proposed to use a staggered data structure (as shown at the bottom in below
picture) that can increase the data density by roughly 40%, without adding too much
25   complexity to the system. Lines connecting nearest neighbour data bits have an
angle of approximately 45 degrees with the edges of the data structure or data page.

The basic difference is that due to a more closed packing more bits can be stored in
the same area, whereas the distance between the individual data bits is still
30   reasonably large to avoid overlap.
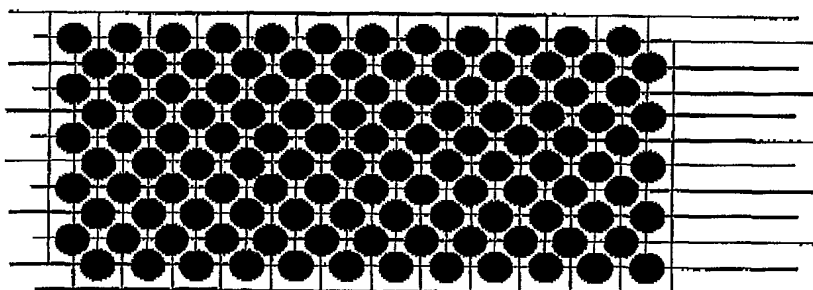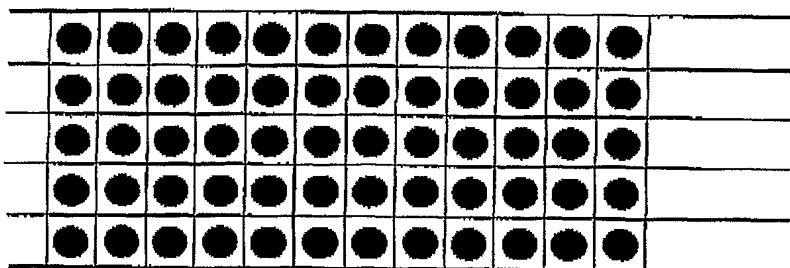
To realize such a system, a data encoder having encoder elements for encoding a data beam (for example a 2 dimensional light modulator) needs to have a similar staggered structure, which doesn't actually pose any severe technical properties. On the other hand a pixelated photo-detector having detector elements organized in a staggered structure needs to be used. A device like this is already on the market and being used in digital camera's (like FUJI Finepix CCD-series). For reference we have included a picture of such a detector.

♦ CONVENTIONAL CCD   ♦ SUPER CCD
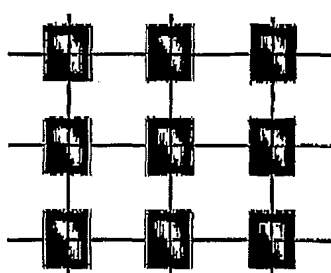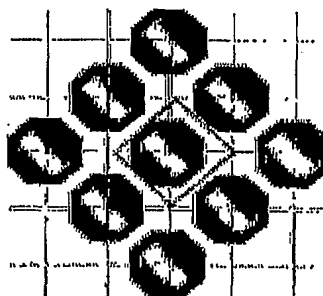
In conclusion, the proposed method can lead to a significant increase of the attainable data density in a practical system, or one can use this enhancement to reduce the size of the components needed.

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CLAIMS:

1. A holographic data storage system for reading and/or recording data bits being organized in a staggered data structure.

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2. A holographic data storage device for reading from and/or recording data pages in a holographic data storage medium, said device comprising a pixelated detector and a data encoder for generating an encoded data beam, said data encoder having individual encoder elements organized in a staggered structure.

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3. A holographic data storage device for reading from and/or recording data pages in a holographic data storage medium, said device comprising a pixelated detector and a data encoder for generating an encoded data beam, said pixelated detector having individual detector elements organized in a staggered structure.

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4. A holographic data storage medium comprising datapages having individual data bits organized in a staggered data structure.

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Phase-Retrieval in Volumetric
Holographic Data Storage

Wim Coene and Sjoerd Stallinga

20-11-2003

Abstract

In the recording step for state-of-the-art holographic data-storage, the wavefronts are modulated in amplitude *only* by the spatial light modulator (SLM) in accordance with the 2D bit-pattern of the considered data page to be stored. The detection process on the CCD for the reconstruction step in holographic data storage is not sensitive to the phase of the wavefront after the SLM. We propose an adapted hardware set-up for the reconstruction step which enables phase-retrieval of the wavefront behind the SLM. This makes it possible to store two data pages instead of one per (angular or shift) multiplexing setting. Although this principle is in general possible for other multiplexing methods, we have described it in more detail for the case of angle-multiplexing. Two methods for phase-retrieval are proposed: (1) holographic restoration with an extra reference wavefront; and (2) a phase-stepping procedure.

1   The Problem

In state-of-the-art holographic storage (with angle-multiplexing used as an example), the image captured on the CCD reflects the (squared) amplitude distribution of the wavefront for the data page that was present on the spatial light modulator (SLM) during the recording phase. Note that the holographic recording also stores the phase information of the wavefront behind the SLM into the holographic medium (we will call this wavefront shortly the "SLM wavefront"). However, during recording at the CCD, this phase information is lost. Therefore, in the current state-of-the-art, the SLM wavefront is only meaningfully modulated in amplitude, *not* in phase.

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2   The Current Idea in a Nut-Shell

The current idea is to extend the reconstruction procedure in holographic storage so that also the phase-information of the SLM wavefront can be restored. This doubles the information density that can be restored with one angle (or multiplexing setting) as used in the reconstruction with angle-multiplexing. We will address two ways of phase-retrieval:

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  • phase-retrieval through an extra holographic restoration set-up added to the reconstruction procedure;
  • phase-retrieval through a phase-stepping procedure.

3   Prior Art: Holographic Data Storage

3.1   Holographic Recording of a Data Page

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The recording procedure for a single data page is shown in Fig. 1 (see also Fig.1 in [1]). The laser beam is split into two parts by a (non-polarizing) beam-splitter (NPBS). On top, we have the so-called "signal arm" where the wavefront passes through a spatial light modulator (SLM) (e.g. an LCD) where typically the amplitude of the SLM pixels is modulated in correspondence with the bits of the data page that is currently to be stored, yielding the SLM wavefront denoted ψ_{SLM}. At the bottom, we have the so-called "reference arm", where the wavefront passes through a grating yielding a reference wavefront denoted ψ_{ref} (which

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is a plane wave $\exp\{2\pi i \mathbf{K} \cdot \mathbf{r}\}$ with a wave vector $\mathbf{K}$ that can be tuned by the grating). The two wavefronts of the signal arm and the reference arm interfere in the holographic medium: the position-dependent part of the dielectric constant in the medium $\epsilon(\mathbf{r})$ is then proportional to $|\psi_{SLM} + \psi_{ref}|^2$. For recording of multiple data pages, the wave vector is set by the grating at $\mathbf{K}^j$ for the j-th page; with the SLM wavefront for the j-th page denoted ψ^j_{SLM}, the position dependent part of the dielectric constant of the medium after recording of the multiple pages

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becomes proportional to:

$$\epsilon(\mathbf{r}) \propto \Sigma_j |\psi^j_{SLM} + \exp\{2\pi i \mathbf{K}^j \cdot \mathbf{r}\}|^2 \qquad (1)$$

3.2   Holographic Reconstruction of a Data Page

The reconstruction procedure for a data page is shown in Fig. 2. This is called the "probe arm" in [1]. A wavefront is passed through a grating that is tuned

30
to generate a plane wave with the proper wave vector $\mathbf{K}^j$ for the reconstruction of the j-th data page. The latter wave is denoted ψ_{ref} and must be equal to the reference wave that was used to record the data page. The wave propagates through the holographic medium where it is diffracted: it generates behind the

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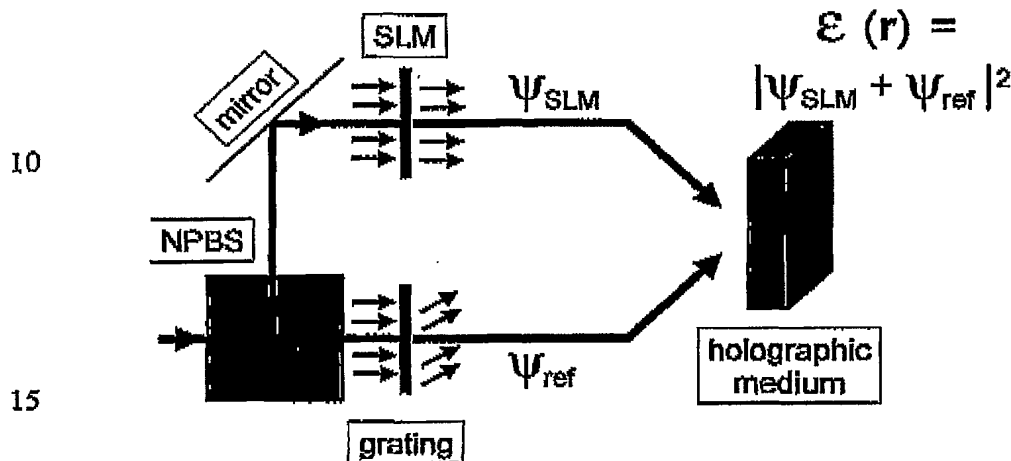
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Figure 1: Prior Art. Recording step for one data page of information in holographic storage (with angle-multiplexing).

medium a wavefront that equals the SLM wavefront that was realized for the j-th data page during the recording of the data page. The SLM wavefront is imaged onto a CCD array, where the modulus squared of the wavefront $|\psi_{SLM}^j|^2$ is detected.

Note that instead of the SLM wavefront itself it is also possible to record the 2D Fourier transform of the wavefront into the holographic memory (the so-called "Fourier-plane" set-up). Our idea applies to both architectures.

4 New Idea

4.1 Phase-Retrieval through Holographic Restoration

4.1.1 Hardware Set-Up

We propose a new reconstruction procedure as shown in Fig. 3. There is a (non-polarizing) beam splitter (NBPS) yielding two separate light paths with mutually coherent wavefronts. Note that the bottom path is identical to the "probe arm" of the state-of-the-art reconstruction of Fig. 2 (apart from the registration on the CCD): thus, it reproduces the SLM wavefront ψ_{SLM} behind the holographic

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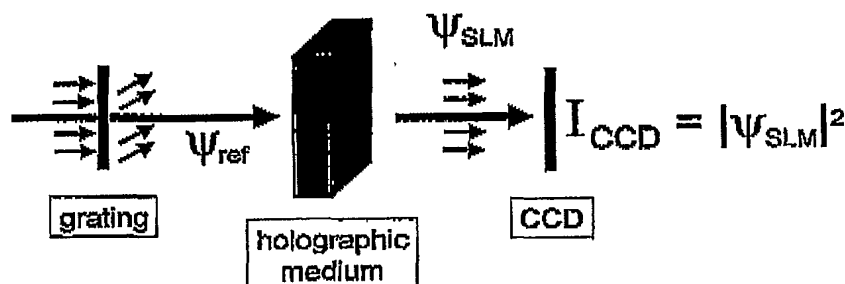
5

Figure 2: Prior Art. Reconstruction step for one data page of information in holographic storage (with angle-multiplexing).

15

medium. In addition, the current idea comprises an extra light path drawn at the top of Fig. 3. This top light path produces a wavefront that passes through another grating (called "grating-B") that yields a plane wave with a wave vector denoted K_{hol}. The resulting (plane) wavefront is denoted ψ_{hol}. The wave vector K_{hol} is not at all related to that of the reference wavefront ψ_{ref} needed for the holographic reconstruction. The choices that determine K_{hol} will be discussed later in relation to the required post-processing of the CCD image. Next, the wavefronts of the two branches, that is, ψ_{SLM} and ψ_{hol}, are made to interfere before registration on the CCD. Now, contrary to the state-of-the-art, the CCD records the power in the resulting wavefront, that is: $I_{CCD} = |\psi_{hol} + \psi_{SLM}|^2$. Note that this step as such is not new on its own, since it is a well known technique in for instance phase-retrieval for off-axis electron holography [2]. It is the combination of this holographic phase-retrieval with holographic data storage that we claim as new insight.

4.1.2 Post-Processing on CCD Image

The different signal processing steps that are to be carried out on the CCD image are described in Fig. 4. First, for the reconstruction of the j-th data page, we rewrite the wavefront that is incident on the CCD as (with R the 2D position coordinate in the plane of SLM and CCD):

$$\psi_{CCD}(R) = \psi^j_{SLM}(R) + \exp\{2\pi i K_{hol} \cdot R\} \exp\{i\phi\}. \qquad (2)$$

In the above equation, ϕ represents a constant overall phase-difference between the two interfering wavefronts: for instance, it might be due to non-equal distances

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$$I_{CCD} = |\psi_{hol} + \psi_{SLM}|^2$$
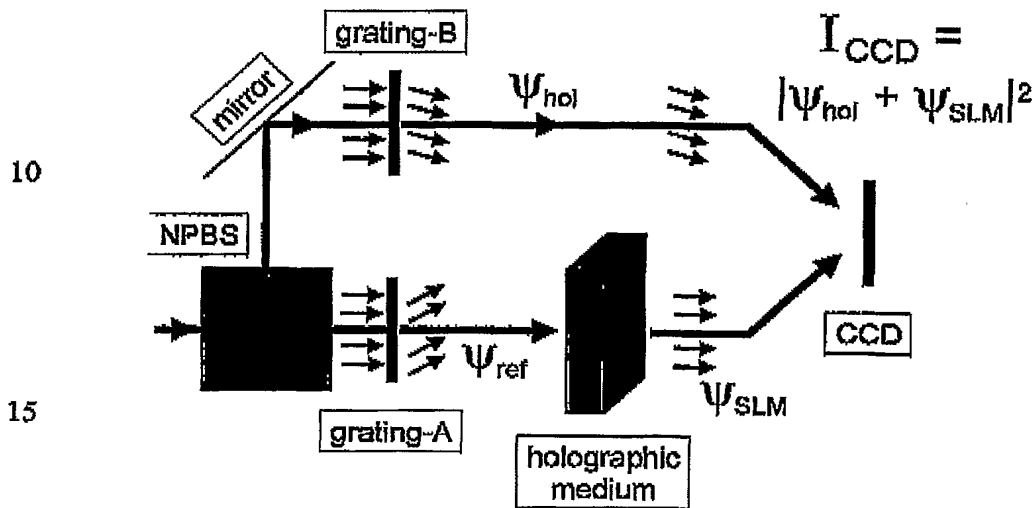
Figure 3: Current ID. Set-up for reconstruction with phase-retrieval of one data page of information in holographic storage (with angle-multiplexing).

20

for the two light-paths of Fig. 3. The image intensity recorded on the CCD then becomes:

$$
\begin{aligned}
I_{CCD}(\mathbf{R}) &= 1 \\
&+ |\psi_{SLM}^j(\mathbf{R})|^2 \\
&+ \psi_{SLM}^j(\mathbf{R}) \; \exp\{-2\pi i\, \mathbf{K}_{hol} \cdot \mathbf{R}\} \; \exp\{-i\phi\} \\
&+ \psi_{SLM}^j(\mathbf{R})^* \; \exp\{+2\pi i\, \mathbf{K}_{hol} \cdot \mathbf{R}\} \; \exp\{+i\phi\}. \qquad (3)
\end{aligned}
$$

The first post-processing step comprises a 2D FFT (real-to-complex) in the "forward" direction applied on $I_{CCD}(\mathbf{R})$. This yields formally (with Ω the 2D frequency vector in the 2D Fourier plane):

$$
\begin{aligned}
\tilde{I}_{CCD}(\Omega) &= FT_{\mathbf{R}\to\Omega}\{I_{CCD}(\mathbf{R})\} \\
&= CB(\Omega) + SB^+(\Omega) + SB^-(\Omega) \qquad (4)
\end{aligned}
$$

where CB stands for *Central Band* and SB for *Side Band* in the Fourier transform of the CCD image. The central band corresponds with the Fourier transform

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of the first two terms in Eq. (3): it contains the auto-correlation of the SLM wavefront (which equals the CDD image intensity in the state-of-the-art solution). The sidebands SB^+ and SB^- correspond to the Fourier transform of the third and fourth terms in Eq. (3). Due to the auto-correlation, the band-width of the central band is twice as large as the band-width of each of the sidebands. The magnitude of the wave vector K_{hol} is chosen such that in the Fourier spectrum the sidebands and central band do not overlap. The azimuth of the wave vector

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K_{hol} can be chosen freely: in Fig. 4 it is chosen such that the sidebands are positioned along the horizontal axis in the Fourier spectrum, which corresponds to a fringe-pattern recorded on the CCD with a vertical orientation of the fringes. But other choices are possible, for instance diagonally oriented fringes leading to sidebands in opposite corners along one of the diagonals in the 2D Fourier plane. Further note that both sidebands are each other's complex conjugate, as must be, since they originate from a Fourier transform applied on a real-valued image. In other words, both sidebands carry exactly the same information.

15

The second post-processing step comprises a selection of one of the sidebands (say SB^+), and centering operation with respect to its center point, which is equal to K_{hol}:

$$SB^+(\Omega - K_{hol}) = \tilde{\psi}^j_{SLM}(\Omega). \qquad (5)$$

Note that the information in the central band is not used at all. The third and last post-processing step comprises a 2D Fourier transform (complex-to-complex,

20

and in the "backward" direction, from Ω to R), yielding the complex-valued wavefront $\psi^j_{SLM}(R)$ as:

$$\psi^j_{SLM}(R) = FT_{\Omega \to R}\{SB^+(\Omega - K_{hol})\}. \qquad (6)$$

Eq. (6) yields both amplitude and phase information of the SLM wavefront for the j-th data page that is stored in the holographic memory.

25

4.1.3 Requirements put on the CCD Sensor

The resolution of the CCD must be high enough to be able to record the information that is present in the sidebands. Since the state-of-the-art recording on the CCD only records the central band, and since the bandwidth of the central band is twice that of the sideband, the current ID needs a CCD with pixels that are twice as narrow as for the state-of-the-art solution. Note that this extra resolution is only needed in the direction that is orthogonal to the fringes (e.g. the horizontal

30

direction as is shown in Fig. 4). A solution could be to use rectangularly shaped pixels on the CCD, with a horizontal to vertical aspect ratio of a factor two.

5
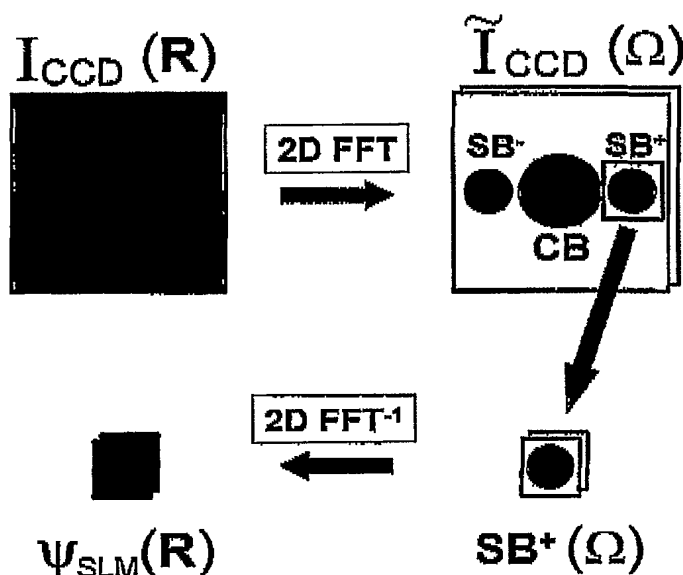
Figure 4: Current ID. Successive steps in post-processing on CCD-image for holographic reconstruction with phase-retrieval of one data page. (a) 2D forward FFT; (b) selection of side-band (SB^+); (c) 2D backward FFT.

4.1.4 Use of the Central Band

As described above, in the holographic restoration, the central band information is discarded. A method to use that information as side-information is proposed in [3] for the case of off-axis electron holography. It comprises a signal processing step where the auto-correlation can yield additional information on the amplitude of the SLM wavefront. This might be beneficial for cases of low signal-to-noise ratios.

4.1.5 Variations on the Theme

Other related details that came up are:
• use of a CCD with square pixels, and detection of more than one page on a single CCD image, where the different pages must have different wave vectors K_{hol} in the holographic restoration. In this case, the central bands are superimposed and are more difficult to be used in the post-processing.
• other phase-retrieval methods are also possible, like detection of a series of CCD

5 images for the same data-page but at different settings of an optical parameter (like defocus or 2-fold astigmatism). Such methods are well known in the area of phase-retrieval for high resolution transmission electron microscopy (HR-TEM) [4].

4.2 Phase-Retrieval through a Phase-Stepping Procedure

10 A different method of phase retrieval (that we propose in this ID) uses the method of phase stepping. Such methods are well-known in the field of interferometry [5]. Now the additional wavefront ψ_{hol} is uniform, i.e. we select $K_{hol} = 0$. The resulting intensity measured on the CCD is then:

$$I^{\phi}_{CCD}(\mathbf{R}) = 1 + |\psi^j_{SLM}(\mathbf{R})|^2 + 2|\psi^j_{SLM}(\mathbf{R})| \cos[\phi_{SLM}(\mathbf{R}) - \phi], \quad (7)$$

15 where $\phi_{SLM}(\mathbf{R})$ is the phase of the wavefront $\psi_{SLM}(\mathbf{R})$ that is to be reconstructed. This phase can be retrieved by a phase stepping procedure. In this procedure the phase ϕ of ψ_{hol} is set to different values in a controlled way, and $I^{\phi}_{CCD}(\mathbf{R})$ is measured for each phase value ϕ. The phase of the reconstructed wavefront can be determined from the measured values $I^{\phi}_{CCD}(\mathbf{R})$. The phase ϕ of ψ_{hol} can be varied by changing the optical path length of the arm of the wavefront ψ_{hol}, by e.g. displacing a mirror in this arm with a piezo-element.

For example, consider the case where the SLM sets the phase $\phi_{SLM}(\mathbf{R})$
20 equal to 0 or π. This binary phase front can be retrieved by stepping through two phases ϕ_1 and ϕ_2, where $\phi_1 \neq (2l+1)\pi/2$ $(l = 0, 1, 2, 3, \ldots)$ and $\phi_2 - \phi_1 = \pi$. In that case the difference between the two measured intensity distributions yields:

$$
\begin{aligned}
I^{\phi_1}_{CCD}(\mathbf{R}) - I^{\phi_2}_{CCD}(\mathbf{R}) &= 4|\psi^j_{SLM}(\mathbf{R})| \cos[\phi_{SLM}(\mathbf{R}) - \phi_1] \\
&= \begin{cases} +4|\psi^j_{SLM}(\mathbf{R})| \cos(\phi_1), & \text{if } \phi_{SLM}(\mathbf{R}) = 0, \\ -4|\psi^j_{SLM}(\mathbf{R})| \cos(\phi_1), & \text{if } \phi_{SLM}(\mathbf{R}) = \pi. \end{cases}
\end{aligned} \quad (8)
$$

25 It follows that the sign of the intensity difference determines the value of the sought-for phase $\phi_{SLM}(\mathbf{R})$ (which is assumed to be binary in this simple example). Phase stepping methods requiring 4 to 5 steps are generally sufficient to retrieve an arbitrary (non-binary) phase front [5].

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References

[1] G. Barbastathis and D. Psaltis, *Volume Holographic Multiplexing Methods*, in "Holographic Data Storage", Springer Series in Optical Sciences (eds. H.J. Coufal, D. Psaltis, G.T. Sincerbox), 2000, pp. 21-61.

[2] H. Lichte, Adv. Opt. Electr. Microsc. Vol. 12 (1991), p. 25.

[3] W. Coene, "Method for Image Reconstruction in a High-Resolution Electron Microscope", US-patent US5432347, 1995.

[4] Special Issue of Ultramicroscopy on Brite-Euram Project No. 3322, "Towards One-Ångstrom Resolution", Ultramicroscopy, Vol. 64, 1996.

[5] *Optical Shop Testing*, D. Malacara, ed. , John Wiley & Sons, New York, 1992.

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